

Exposure Time Calculator for LUCIFER

- USER MANUAL -

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Abstract

The exposure time calculator (ETC) roughly calculates the exposure time of LUCIFER at the Large Binocular Telescope (LBT). There is a wide choice of different model spectra available (e.g. different main sequence stars). It is also possible to select a blackbody spectrum or a single-line spectrum as an object spectrum.

The main calculations are written in Python and the user interface is web-based. The web interface provides an additional graphical output that shows the SNR versus Wavelength in spectroscopic mode or SNR vs. exposure time in case of a selected imaging mode.

This document presents the basics of the exposure time calculator. The formulae of the ETC and the main characteristics of LUCIFER are described in detail.

1 Basics

1.1 List of Abbreviations and Acronyms

AO	adaptive optics
CWL	central wavelength
DARK	dark current
DIT	detector integration time
e.m.	electro magnetic
ETC	exposure time calculator
EW	entrance window
FWHM	full-width at half-maximum
HTML	hyper text markup language
LBT	Large Binocular Telescope
LUCIFER	LBT NIR Spectroscopic Utility with Camera and Integral Field Unit for Extragalactic Research
PSF	point spread function
QE	quantum efficiency
RON	readout noise
SNR	signal-to-noise ratio
SNR _{τ}	signal-to-noise ratio for exposure time τ
SNR _{DIT}	signal-to-noise ratio for one DIT

1.2 The Exposure-Time-Calculator

1.2.1 The Formulae

This program will be used by observers for scheduling their observations with LUCIFER. The following fixed parameters

- telescope (transmission, light-collecting area, reflectivity, ...)
- transmission of the instruments (entrance window, lenses, ...)
- quantum efficiency (QE) of the detector

and user-defined parameters

- object (geometry, spectrum, magnitude)
- camera (scale)
- filter
- grating, slit width (spectroscopic mode)
- atmospheric conditions (airmass, water vapor, sky background, seeing)
- adaptive optics (is loop closed, Strehl ratio)
- exposure parameters (detector integration time, total exposure time)
- signal-to-noise ratio

are used to calculate two auxiliary values:

$$E = T_{\text{atm}} \cdot T_{\text{tel}} \cdot T_{\text{inst}} \cdot T_{\text{filt}} \cdot \text{QE} \quad (1)$$

$$F = F_0 \cdot 10^{-\frac{\text{mag}}{2.5}} \quad (2)$$

- F_0 : flux density for Vega at $\lambda = 550 \text{ nm}$
 $F_0 = 3.56 \cdot 10^{-11} \frac{\text{W}}{\text{m}^2 \cdot \text{nm}}$ [FLUX95]
- mag : magnitude of the object
- QE : quantum efficiency of the detector
- T_{atm} : transmission of the atmosphere
- T_{tel} : transmission of the telescope
- T_{inst} : transmission of the instrument (without any filter and grating)
- T_{filt} : transmission of the filter used

The number of photons that are detected per second can be calculated with (1), (2) and the following formula [ESO-HP]:

Table 1: Formulae for calculating the number of photons from the source

Observing mode	point source	extended source
Imaging	$\frac{N}{\tau} = \frac{F \cdot \Delta_i \cdot E \cdot S}{P}$	$\frac{N}{\tau} = \frac{F \cdot \Delta_i \cdot E \cdot S \cdot \Omega_i}{P}$
Spectroscopy	$\frac{N}{\tau} = \frac{F \cdot \Delta_s \cdot E \cdot S}{P}$	$\frac{N}{\tau} = \frac{F \cdot \Delta_s \cdot E \cdot S \cdot \Omega_s}{P}$

N	: number of photons	Δ_i	: filter band width
P	: energy of one photon	Δ_s	: spectral resolution
S	: light-collecting area	Ω_i	: scale in imaging mode
τ	: exposure time	Ω_s	: scale in spectroscopy mode

In the near-infrared regime the SNR for the exposure time DIT is given by the formula:

$$\text{SNR}_{\text{DIT}} = \frac{N_{\text{DIT}}}{\sqrt{N_{\text{DIT}} + n_{\text{pix}} \cdot (N_{\text{sky}} + \text{DARK}_{\text{DIT}} + \text{RON}^2)}} \quad (3)$$

DARK_{DIT}	: dark current for 1 DIT
n_{pix}	: number of integration pixels ¹
N_{sky}	: sky signal for 1 DIT
RON	: readout noise
SNR_{DIT}	: signal-to-noise ratio for 1 DIT

In imaging mode the user will be asked for the signal-to-noise ratio for the exposure time τ (SNR_τ). The ETC calculates the necessary exposure time to achieve this SNR_τ (see also formula 3):

$$\tau = N_{\text{DIT}} \cdot \text{DIT} \quad \text{and} \quad \text{SNR}_\tau = \text{SNR}_{\text{DIT}} \cdot \sqrt{N_{\text{DIT}}} \quad (4)$$

$$\rightarrow \tau = \left(\frac{\text{SNR}_\tau}{\text{SNR}_{\text{DIT}}} \right)^2 \cdot \text{DIT} \quad (5)$$

τ	: total exposure time
DIT	: detector integration time
N_{DIT}	: number of detector integrations
SNR_τ	: signal-to-noise ratio for exposure time τ
SNR_{DIT}	: signal-to-noise ratio for one DIT
SNR	: signal-to-noise ratio for an exposure time of 1 sec

1.2.2 The Telescope

Mirrors

Both LUCIFER instruments are going to be first-light instruments for the Large Binocular Telescope (LBT) at the bent Gregorian foci. This means, that

¹In imaging mode n_{pix} of a point source is calculated within a 2 FWHM diameter aperture: $n_{\text{pix}} = \pi \left(\frac{\text{seeing}}{\text{scale}} \right)^2$. In spectroscopic mode the program uses $n_{\text{pix}} = 2 \cdot \frac{\text{seeing}}{\text{scale}}$. For an extended source n_{pix} is set to 1 for both dimensions of the source.

the light is reflected three times before entering the cryostats. If we optimistically assume a reflectivity of 90 % for each mirror, we get a total efficiency of 0.729 at the bent Gregorian foci.

Adaptive Optics (AO)

The LBT will provide a deformable secondary mirror for AO observations. For this reason the ETC can handle both a seeing-limited PSF and a diffraction-limited PSF (1.2.3). If the loop is closed, different Strehl ratios are possible. This depends on the environmental conditions (seeing, ...). Therefore the value of this parameter is continuously changeable.

1.2.3 Point-Spread-Function

Diffraction Limited Mode

For comparing the peak intensity of a diffraction-limited optical system with a real system the *Strehl parameter* was introduced.

$$\text{Strehl} = \frac{I_{\text{obs}}}{I_{\text{theo}}} \quad (6)$$

This parameter is the ratio of the observed peak intensity at the detection plane of a telescope or other imaging system from a point source compared to the theoretical maximum peak intensity of a perfect imaging system working at the diffraction limit. In diffraction limited mode the PSF is approximately composed of two functions:

1. The core: This is an airy function of the telescope multiplied by the Strehl ratio

$$I_{\text{Airy}}(r) \sim \text{Strehl} \cdot \left(\frac{2 \cdot \text{Bessel}(x)}{x} \right)^2 \quad (7)$$

Bessel(x) is the order 1 Bessel function of the first kind.

2. The halo: It is given by a Moffat function (9) multiplied by (1-Strehl)

$$I_{\text{Moffat}}(r) \sim (1 - \text{Strehl}) \cdot I_{\alpha, \beta}(r) \quad (8)$$

This combined AO-PSF is shown in Figure 1.

Seeing Limited Mode

The simulation uses two different point spread functions. The PSF is approximated by a Moffat function (9) in the seeing-limited case. In contrast to a Gaussian-shaped function it contains more light in the wings. The parameter β is responsible for the amount of light in the wings. $\beta = 2.5$ is used for point sources.

$$I_{\alpha, \beta}(r) = \frac{\beta - 1}{\pi \alpha^2} \left(1 + \frac{r^2}{\alpha^2} \right)^{-\beta} \quad (9)$$

- $I_{\alpha, \beta}(r)$: Intensity at the distance r with parameters α and β
- α : Another parameter (is used to fix the FWHM for a given β)
- β : Parameter to fix the amount of light in the lobes
- r : Distance to the center ($r = \sqrt{x^2 + y^2}$)
- $FWHM$: $2\alpha\sqrt{2^{1/\beta} - 1}$

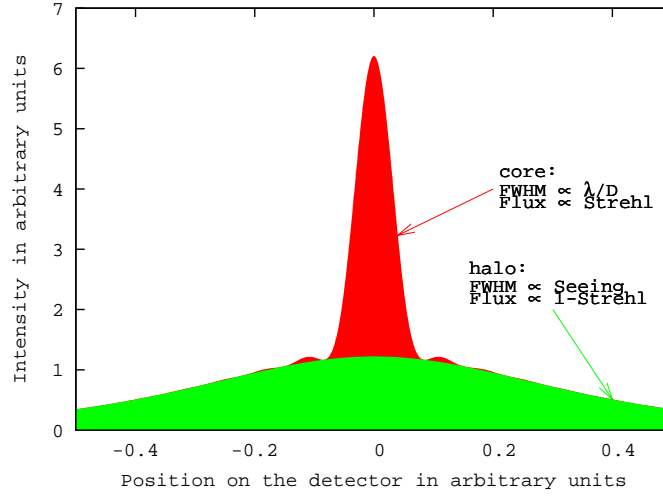


Figure 1: Simplified description of an AO-PSF: It is built by a core (Airy function) and a halo (Moffat function)

1.2.4 Objects

Besides the choice of the source's size (point source or extended source) the observer can select one out of three different types of spectra:

1. Model spectrum (stellar, galaxy or uniform template)
2. Blackbody spectrum
3. Gaussian-shaped emission line

In imaging mode the stepping of the spectra is 0.5 nm. This stepping is adjusted to the spectral resolution in spectroscopic mode.

Template Spectra

6 different model spectra representing various main sequence stars are available. These are [STERNS]: B0V, A0V, F0V, G0V, K0V, M0V (Figure 2).

Their flux densities are normalized to

$$f(\lambda = 550 \text{ nm}) = 3.66 \cdot 10^{-11} \text{ W m}^{-2} \text{ nm}^{-1} \quad (10)$$

In addition, 4 different galaxy template spectra are available (Figure 3 and [GALAXS]). If a spectrum is allowed to be redshifted the filename must include the phrase 'galaxy' at any position.

The transformed spectra are calculated by the definition of the redshift:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} \rightarrow \lambda = (z + 1)\lambda_0 \quad (11)$$

- z : redshift
- λ : measured wavelength
- λ_0 : rest wavelength

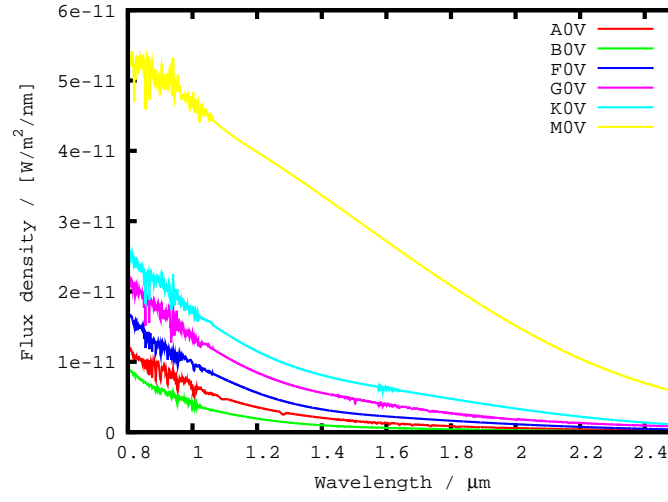


Figure 2: The six available stellar spectra

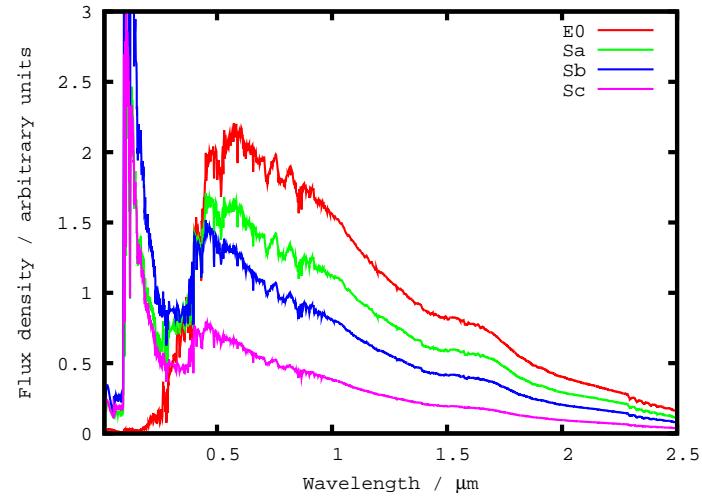


Figure 3: The four available galaxy spectra at redshift $z=0$.

Finally, a uniform spectrum can be used. The first step of creating such a spectrum (constant flux density for all wavelengths) is to calculate the total flux (in the given band-pass) for a uniform spectrum with an arbitrary flux density. After that the flux is calibrated to the target magnitude given by the user.

Blackbody Radiation

The blackbody spectrum is another option that can be chosen. The flux density is calculated as a function of wavelength (12) for the user-defined temperature (T).

$$f(\lambda) \propto \frac{1}{\lambda^5 \cdot \exp\left(\frac{hc}{k\lambda T_{BB}}\right) - 1} \quad (12)$$

- h : Planck's constant $h = 6,62607 \cdot 10^{-34}$ Js
- c : velocity of light $c = 2.9983 \cdot 10^8 \frac{m}{s}$
- k : Boltzmann's constant $k = 1,3807 \cdot 10^{-23} \frac{J}{s}$
- T_{BB} : Blackbody temperature

After that calculation the flux is normalized to the magnitude given by the user.

Gaussian-Shaped Emission Line

The last selectable standard spectrum is a gaussian-shaped emission line. The parameters are: central wavelength, FWHM and total flux. The magnitude of the source is not a free parameter anymore due to the total flux given by the user:

$$f(\lambda) = FLUX \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(\lambda-\Gamma)^2}{2\sigma^2}} \quad (13)$$

σ is given by FWHM/2.35, FLUX the total flux and Γ the central wavelength.

1.2.5 Target Magnitude

The input of the source magnitude (available for template spectra or blackbody only) have to be done in Vega magnitudes.

1.2.6 Entrance Window

LUCIFER is equipped with an entrance window tilted by 15° . It reflects the visible light to a wavefront sensor. Two different coatings are available. The main parameters are listed in Tab 2 while the plots can be found in Appendix C:

Table 2: Available entrance windows

	Window #1	Window #2
50% cut on	882 nm	955 nm
transmission at 532 nm	0.42%	0.12%

1.2.7 Filter

LUCIFER’s ETC uses transmission data of all filters measured by the manufacturer [BARR]. The additional numbers are the identifiers for the filters. They are stored in wavelength steps of 0.5 nm as well as the previous wavelength-dependent datasets. The transmission curves of these broadband filters are shown in Figure 4. All available filters (including the narrowband filters) are shown in Appendix A.

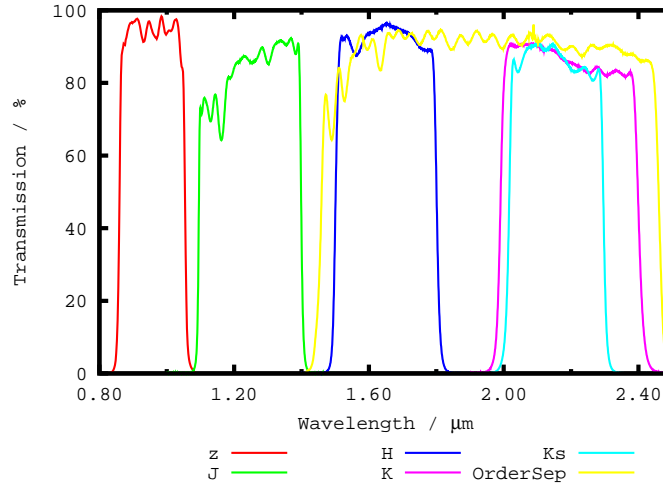


Figure 4: Broadband filters used by LUCIFER

The optical filters U, B, V, R and I can be chosen for the input of the object’s magnitude only. They are originally described in steps of 10 nm (U) and 20 nm (B, V, R and I) [FIL-HP]. By linear interpolation the sampling was increased to 0.5 nm.

1.2.8 Cameras

Three different cameras can be used with LUCIFER. The collimator lenses, mirrors and each camera results in three total efficiencies for each camera. These values are shown in Table 3. One can read off the efficiency of each optical element in [ACC-RE].

Table 3: Efficiencies of the system camera and collimator in different wavelength regimes

Camera	z	J	H	K
N1.8	0.49	0.52	0.57	0.61
N3.75	0.57	0.63	0.68	0.73
N30 (zJ with ADC)	0.37	0.43	0.63	0.68

The image scale of each camera is listed in Tab. 4.

Table 4: Image scale of each camera

Camera	Scale ["/pix]
N1.8	0.25
N3.75	0.12
N30 (zJ with ADC)	0.015

1.2.9 LUCIFER 1 and LUCIFER 2

Both instruments are identical, their detectors, however, have different efficiencies. The efficiency curves are shown in Fig. 5

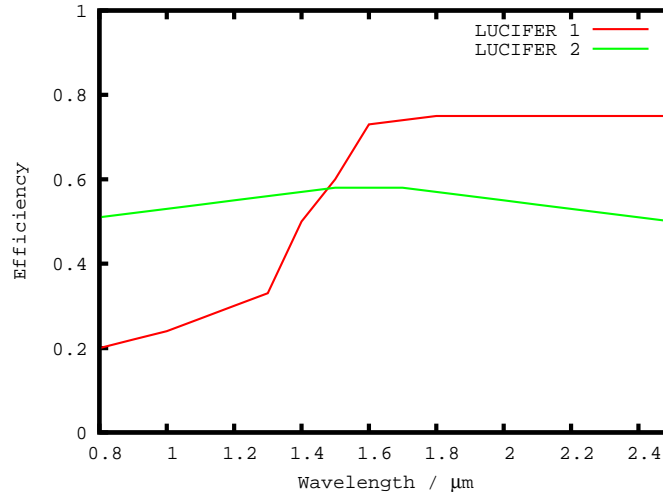


Figure 5: The efficiency of the two LUCIFER detectors versus the wavelength. The different detectors are color coded.

1.2.10 Gratings

Three gratings are installed in LUCIFER. All of them were tested for their efficiencies by the manufacturer. The company measured in a Littrow setup. LUCIFER reaches about 90% ([FDR-OP]) of the nominal efficiencies because it is not working under Littrow conditions. See Appendix B for the plots and ASCII-files.

- **High-Dispersion grating (HD-grating)** with 2101/mm.
- **H+K-grating** with 2001/mm
- **Ks-grating** with 1501/mm

1.2.11 Water vapor in the Atmosphere

The water vapor in the atmosphere is the main reason for absorbing light in the near-infrared and infrared. The transmission of light for three different water-vapor levels in the wavelength range from 0.9 μm to 2.5 μm is shown in Figure 6.

The transmittance of the atmosphere for 1 mm, 1.6 mm and 3 mm water vapor [TRANSA] is displayed. In the ETC three different values for the water vapor can be selected: 1.0 mm, 1.6 mm and 3.0 mm.

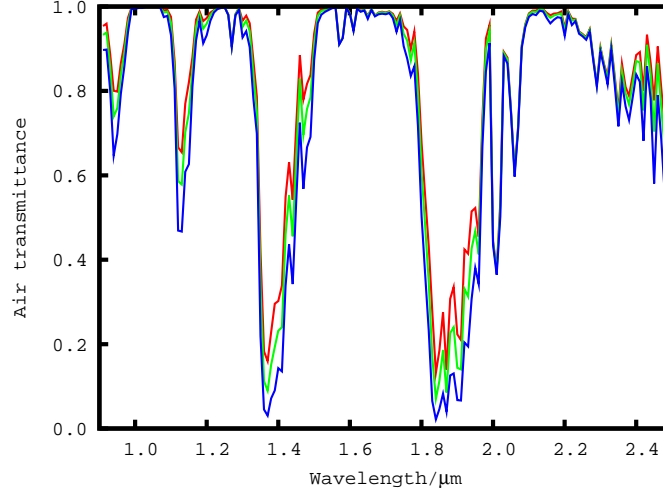


Figure 6: Transmittance vs. wavelength for three different water vapor levels.

1.2.12 Airmass

The airmass is an additional parameter which influences the transmission. The ETC allows six different values for the airmass: 1.00; 1.25; 1.50; 1.75; 2.0; 2.5. The Airmass (AM) scales the number of photons from the sky background with

$$(-0.000278719 \cdot AM \cdot AM \cdot AM - 0.0653841 \cdot AM \cdot AM + 1.11979 \cdot AM - 0.0552132)$$

1.2.13 Sky Background

The sky background in near-infrared regime can rapidly change within hours or even minutes. For that reason the observer can choose between three different possibilities of sky background templates..

Sky Brightness given by the User

The observer can set a brightness of the sky in $\frac{\text{mag(VEGA)}}{\square \text{arcsec}}$ for the zenith. It is the brightness of the sky for the filter used for the observation. The Airmass (AM) scales the number of photons from the sky background with

$$(-0.000278719 \cdot AM \cdot AM \cdot AM - 0.0653841 \cdot AM \cdot AM + 1.11979 \cdot AM - 0.0552132)$$

Background File

Another option is a file. This file contains data from sky background measurements at Mauna Kea for 1.6 mm water vapor and the selected airmass (see Fig. 7).

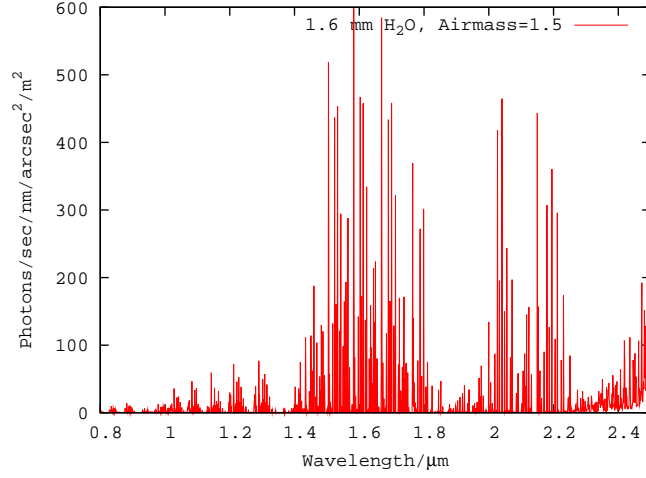


Figure 7: Sky spectrum measured at Mauna Kea

Theoretical Background Spectrum

A theoretical spectrum is the last possibility for choosing a sky background. This spectrum is shown in Figure 8.

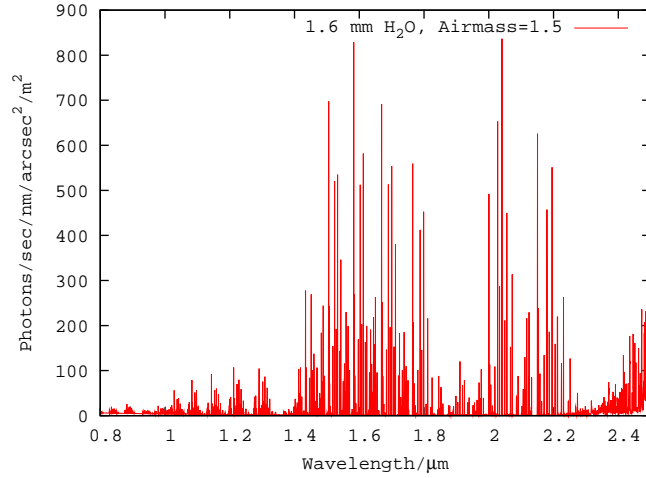


Figure 8: A synthetic spectrum of the sky background

The fundamental parts of this calculation are the OH-line database [OH-LIN, ROUS00] and the transmission data of the atmosphere [AIRTRA]. The ratio of intensities for two lines may change during the night or from observation to observation. This is the reason why it is possible to change the relative intensities via an ini-file. The predefined values are adjusted to Mauna Kea's night sky spectrum [SKYBA]. For modeling the sky background, we assume:

- OH-line absorption due to the light travel through the atmosphere, scaled with T

- thermal emission of a blackbody with a temperature of 250 K, scaled with (1-T)
- zodiacal emission (a blackbody spectrum; T=5800 K)
- increasing intensity with larger zenith distances (described by the *van-Rhijn's function*)

Then the sky background can be described as:

$$N_{\text{sky}} = \frac{T \cdot OH + (1 - T) \cdot BB_{250 \text{ K}} + BB_{5800 \text{ K}}}{\sqrt{\left(1 - \left(\frac{R}{R+h}\right)^2 \cdot \sin^2 z\right)}} \quad (14)$$

N_{sky}	:	number of photons from sky background
T	:	transmission of the atmosphere
OH	:	intensity of the OH-line
BB_x	:	blackbody with a temperature x
R	:	earth radius (~ 6378 km)
h	:	height of emitting layer (~ 100 km)
z	:	zenith distance

1.2.14 Slit Width and Slit Transmission

Slit Width

Four different slit widths between 0.25" and 1.00" can be selected. If the width is smaller than the scale of the camera used the width is set to the scale of the camera.

Slit Transmission

First of all the program calculates the number of photons reaching the slit. After that it computes the number of photons behind the slit. For a point-like source it assumes a PSF like a Moffat or a Moffat + Airy disc. The hatched area in Figure 9 is the relevant area for transmission. The transmitted photons are split into the pixels 1 - 5 (see bottom of Figure 9). For example: if 18 photons are passing the hatched area of the slit, the light will be split up to 4.5 pixels. Pixel 1, 2, 3 and 4 will detect 4 ($18/4.5=4$) photons each. The fifth pixel will count 2 photons.

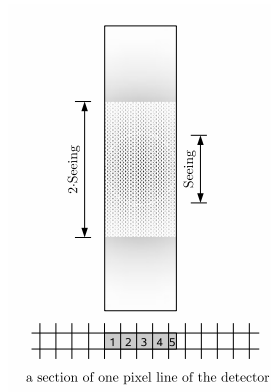


Figure 9: *Top:* Sketch of a slit. The hatched area is used to calculate the transmission of the slit. *Bottom:* The calculated photons are split into the shaded pixels.

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<http://barrassociates.com>

A Filter Curves

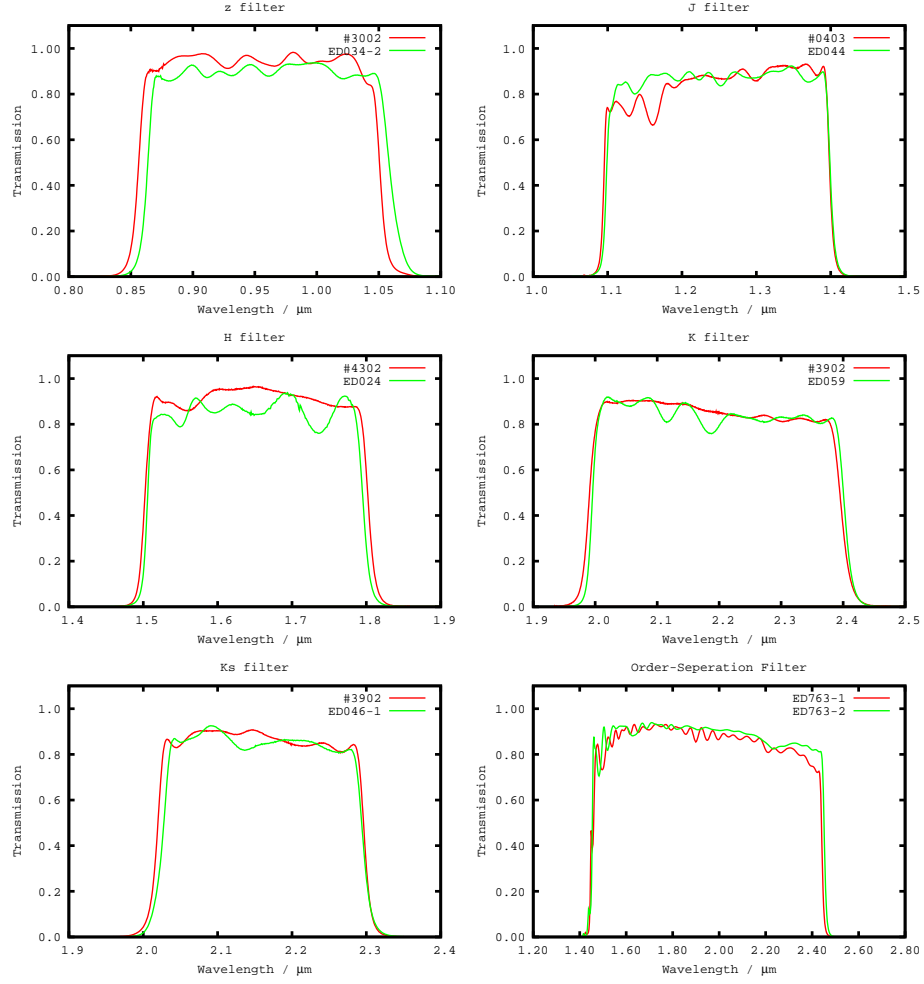


Figure 10: Filter curves of broad-band filters

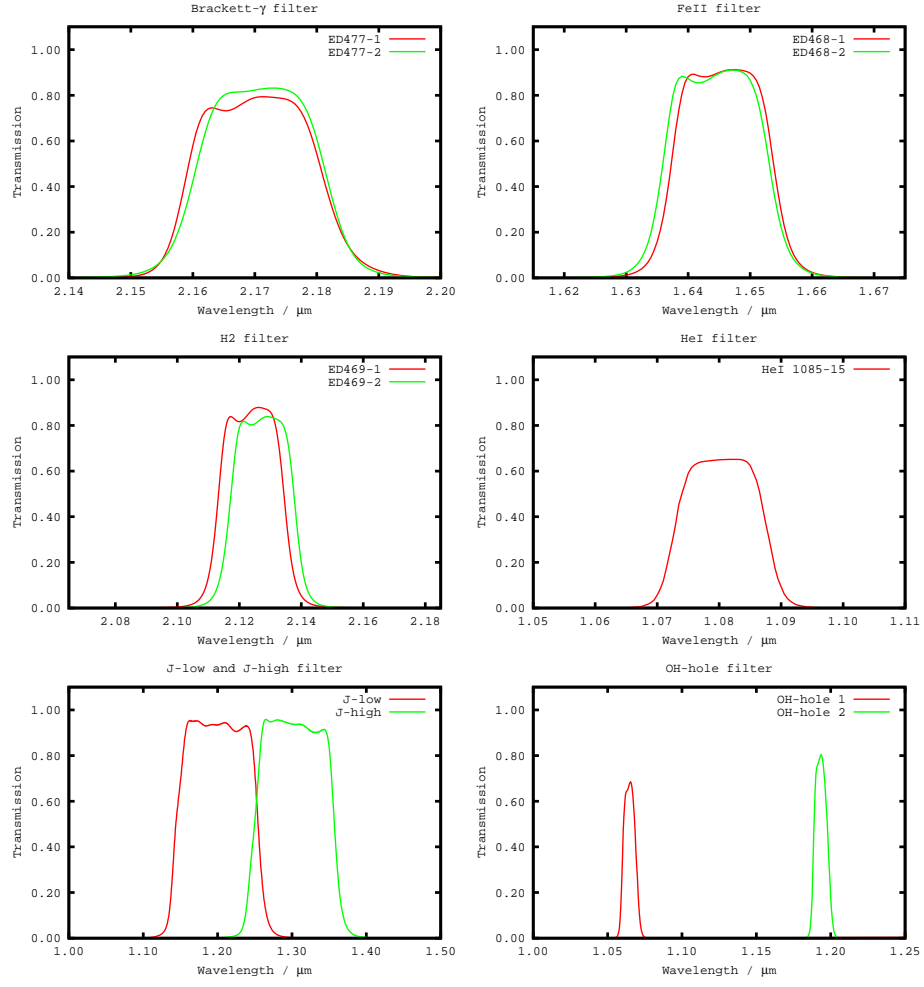


Figure 11: Narrow-band filter curves (Part 1)

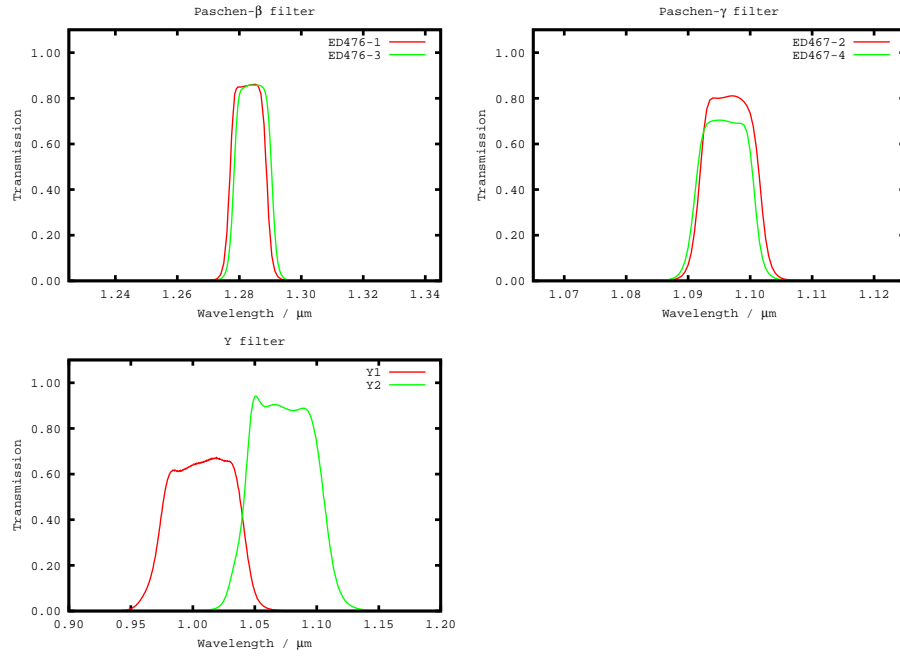


Figure 12: Narrow-band filter curves (Part 2)

B Gratings

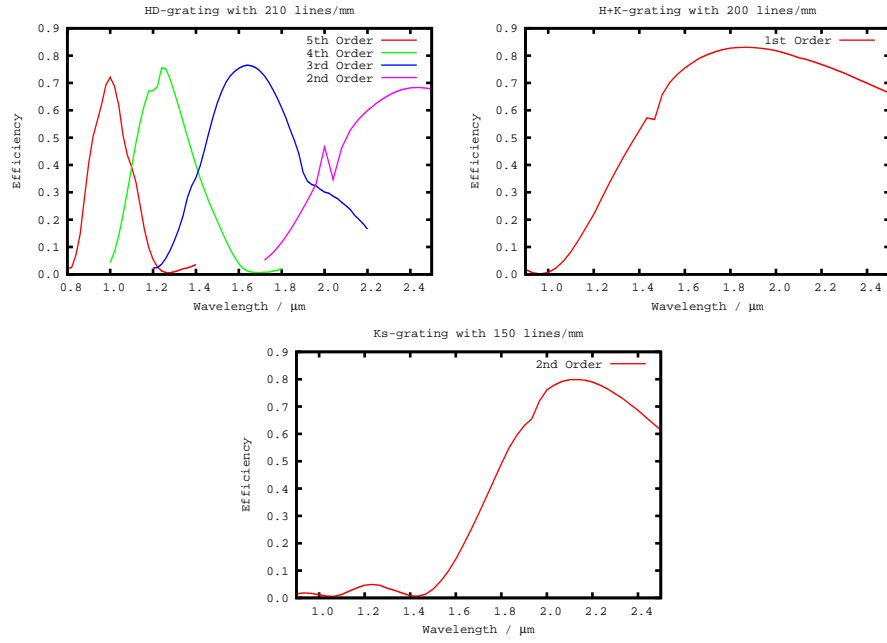


Figure 13: The efficiencies of the gratings vs the wavelength for the Non-Littrow setup. The different orders of each grating are color coded.

C Entrance Windows

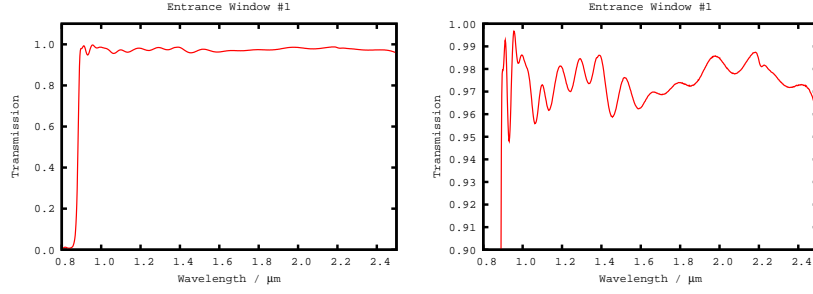


Figure 14: The measured transmission of the entrance window 1. *Left:* The whole transmission curve from zero transmission to full transmission 1. *Right:* The transmission curve zoomed-in to a transmission from 0.90 to 1.00.

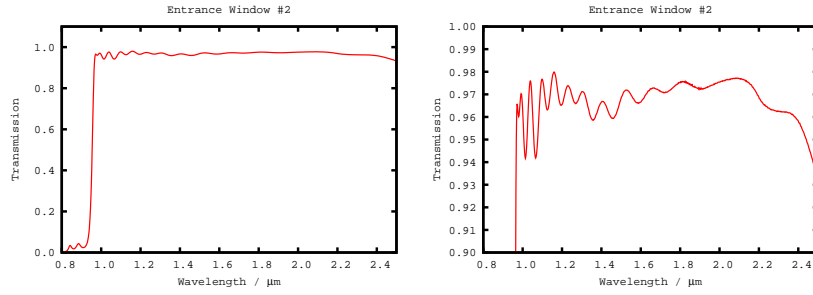


Figure 15: The measured transmission of the entrance window 2. *Left:* The whole transmission curve from zero transmission to full transmission 1. *Right:* The transmission curve zoomed-in to a transmission from 0.90 to 1.00.